Study on Performance Enhancement of Recycled Aggregate Concrete

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論 文 内 容 要 旨

The remarkable growth of the construction industry, in recent decades, the demands for concrete have escalated to about 15 billion tonnes annually, which needs to consume approximately 20 billion tonnes of aggregate each year. The natural aggregate (NA) is being used for construction industry faster than it is being made available and creating a foreseeable shortage in the future. Findings out alternative sources for NA are paid more attention by researchers and stakeholders in construction projects. The rapid urbanization, the end of services of infrastructures, wars, natural disasters and human activities have produced a massive amount of Construction and Demolition Waste (CDW). One of the attractive attentions is to study the solutions for recycling CDW as aggregate in concrete referred to recycled concrete aggregate (RCA). The tendency of using RCA in concrete is growing around the world, which makes construction industry economical and environmentally sustainable. Annually, a thousand studies have been published related to using RCA in concrete (recycled aggregate concrete (RAC)) to promote applications of this material for the construction industry. The barriers of RAC admittedly are the old adhered mortar in RCA which decreased mechanical and durability properties of RAC compared to those of natural aggregate concrete (NAC). Many researchers focused on techniques to enhance the performance of RAC. In current methodologies, although the properties of RAC have been improved, some methods still have negative effects on environmental impacts, more energy consumption, cost saving, or limitations in techniques for treating procedure. Therefore, the aim of this study is to propose several ideas to improve properties of RAC with the lower environmental impacts and simple techniques as follows:

The study presented a new method of combination between RCA and NA in concrete for the purposes of improving the quality of RAC and increasing the amount of RCA in RAC. New methodology significantly enhanced mechanical properties of RAC compared to conventional method. Using new method for RAC, the amount of RCA can be raised up to 50% in concrete while the conventional method limited the amount of RCA should be less than 30%. However, the study expected to raise the amount of RCA in concrete up to 100%. Concrete containing 100% RCA exhibited lower quality than that of NAC. Therefore, it is necessary to proposed another technique for RAC with 100% coarse RCA.

The incorporation of industrial by-products (mineral admixtures) in RAC was proposed to enhance the performance of RAC containing 100% RCA. The by-products including fly ash (FA), silica fume (SF), metakaolin (MK), waste paper sludge ash (PSA) with various proportions (5%, 10%, 15%) in RAC were used in two methods: addition method and replacement method. The effects of by-products on RAC to mitigate the lower quality of RAC were demonstrated. The addition of by-products instead of the addition more cement in RAC for the sake of enhancing the performance of RAC was considered as a promising solution. The use of by-products in RAC resulted in a significant contribution to diminishing CO_2 emission of the final RAC products. The results showed that the incorporation of mineral admixtures in RAC accompanied by the proposed mixing technique could minimize some drawbacks of RAC. It was found that the strength and durability of RAC in the addition method were higher than the replacement method. PSA, MK, and cement improved the strength of RAC better than FA and SF at 7 days. However, at 90 days, FA and MK concrete exhibited higher strength than SF and PSA concrete. The optimum proportions of by-products in RAC were 5% PSA, 10% SF, 15% MK and 15% FA to obtain the highest performance of RAC containing 100% coarse RCA. Moreover, the incorporation of by-products in RAC contributed to enhancement of fire resistance of RAC.

To maximize the effectiveness of mineral admixtures in RAC and reduce the amount of mineral admixture (pozzolanic material) in RAC, the study proposed a new coating technique. This section is an effort to improve the quality of RAC containing 100% coarse RCA by using mineral admixtures (FA, SF, MK), sodium hydroxide, and sodium silicate solution as new treatment solutions. The study proposed three types of treatment solutions including: treatment solution type G (pozzolanic powders, sodium hydroxide, and sodium silicate), treatment solution type S (pozzolanic powders and sodium silicate), treatment solution type SS (only sodium

silicate) at 10, 20, 30% concentration. This study examined performance of RAC after being treated with new treatment solutions. The mechanical properties of RAC were evaluated based on testing of concrete under various conditions. The significant results indicated that sodium silicate combined with pozzolanic materials can improve mechanical properties of RAC containing 100% coarse RCA better than other treatment solutions. Achievements of this approach demonstrated its effectiveness in enhancing the strength of RAC, which is potentially applied to treating RCA for concrete in the future. However, the treatment procedure required the high temperature of 60^{o}C for improving properties of RAC, which led to more energy consumption. It has limitation to apply for larger scales in the construction sites. Therefore, an environmental friendly method should be considered for mitigating environmental impact at ambient temperatures.

An environmental friendly method for enhancing mechanical properties of RAC is introduced by using sodium silicate and SF at the ambient temperature. The proposed method, applied to 100% coarse RCA compared to untreated RAC, can improve compressive strength up to 33-50%, splitting tensile strength 33-41%, and elastic modulus 15.5-42.5%. Tests revealed that the direct tensile strength of RAC and natural aggregate concrete (NAC) were notably lower than the splitting tensile strength, but at 7 days, these values of treated RAC were higher than the splitting tensile strength. From the experimental data, the compressive strength of the treated RAC can be estimated at any age. Besides, the relationships between mechanical properties of treated RAC which were established were significantly different from those of NAC and untreated RAC in previous studies.

In order to diminish the environmental burdens, the study expected to use more types of solid waste in concrete products for construction industry. An idea for reduction of solid waste is to recycle CDW as aggregate, recycle plastic waste as fiber and use industrial by-product (silica fume) as a mineral admixture in RAC. Two type of fibers (Recycled PET Bottles Waste (RPET) and Recycled Woven Plastic Sack Waste (RWS) fiber) used in RAC for the purposed to improve the performance of RAC were presented. The effects of RWS and RPET fibers on RAC were evaluated based on mechanical properties and durability of concrete. The experimental results indicated that RPET and RWS fibers have high alkali resistance in alkaline environments and showed no detectable degradation in RAC at 90 days. The combination between SF and RPET fiber increased 3.6-9% compressive strength, 16.9-21.5% elastic modulus, 11.8-20.3% splitting tensile strength, 7-15% shear strength of RAC in comparison with RAC samples without fibers, while these values in RWS fiber

reinforced RAC were lower. RWS and RPET fibers enhanced the post-cracking behavior of RAC. The contribution of RPET in improvement of the RAC properties was better than that of RWS fiber although the RWS fiber has higher tensile strength than that of RPET fiber. Furthermore, SF and the proposed mixing technique increased the performance of RAC with 100% coarse RCA and compensated the loss of the compressive strength due to RPET and RWS fibers.

From the achievements, it was suggested that further works would be required in this area to pave the way for plastic waste and industrial by-products in practical applications.

（別紙）

論文審査結果の要旨及びその担当者

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論　文　題　目	Study on Performance Enhancement of Recycled Aggregate Concrete (再生骨材コンクリートの性能向上に関する研究)
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論文審査結果の要旨

建物の解体現場などからは大量のコンクリート廃材が排出されているが，廃棄物の有効利用を目指して廃コンクリート塊のリサイクルが進められている．廃コンクリート塊を破砕し，再生骨材として利用する方法が一般的であり，再生骨材は路盤材やコンクリートの骨材として利用されている．再生骨材を用いて作成されたコンクリート(Recycled Aggregate Concrete, 以下 RAC と記す)に関しては, これまでにも数多くの論文が発表されているが, RAC の問題点は，再生骨材の回り古いモルタル部分が強度的に弱く，耐久性も低いため，RAC の性能が砕石骨材を使ったコンクリートに比べて低い点が挙げられている．そこで，本論文では，再生骨材と砕石骨材の混合や再生骨材表面を溶液処理するなどの工夫を施し，RAC の性能を向上させようというものであり，全 7 章から構成される．

第 1 章は緒論である．

第 2 章では，再生骨材と砕石骨材の新しい組み合わせにより，RAC の性能向上について実験的に検討した．コンクリートを作成する際には，粗骨材から細骨材まで粒度分布を有する骨材が必要である．従来は，再生骨材と砕石骨材の質量混合割合のみ注目して RAC を作成していたが，再生骨材の使用量は 30%程度までであった．これに対し，本論文では，粗骨材が強度発現に大きく貢献していることから，粗骨材部分は砕石骨材を使用し，細骨材部分に再生骨材を使用する組み合わせを提案した．その結果，再生骨材の混合割合を従来の 30%から 50%まで増加させることが可能となった．これは本研究で明らかにした新しい成果である．

第 3 章では，RAC の性能を向上と再生骨材の使用割合の増加を目指し，フライアッシュなどの副産物を利用して RAC を作成する方法について検討した．ライアッシュ，シリカフューム，メタカオリン，ペーパースラッジ灰を添加して RAC を作成し，圧縮試験や引張試験を行った結果，ライアッシュおよびシリカフュームを添加した場合，砕石骨材を使用することなく，全て再生骨材を用いても十分な強度が発現されることを確認した．これは，再生骨材の使用量増大と副産物の有効活用に貢献できる優れた成果である．

第 4 章では，再生骨材の表面を溶液で処理してから RAC を作成することにより，RAC の性能向上について実験的に検討した．ケイ酸ナトリウム水溶液にシリカフュームを加えた溶液に再生骨材を浸し，その後，RAC を作成して圧縮試験や引張試験などを実施した結果，RAC の性能が大きく向上することを確認した．これは再生骨材の有効活用を進める上で有益な知見である．

第 5 章では，より環境に優しい表面処理の方法について検討している．第 4 章では再生骨材の表面処理の有効性を確認したが，溶液に浸した再生骨材は 60 度で炉乾燥させなければならないため，エネルギーコストのかかる方法であった．そこで，第 5 章では，初めに 20 度のケイ酸ナトリウム水溶液で再生骨材を処理した後，シリカフュームで再度処理する方法で再生骨材を処理した結果，十分な性能を有する RAC を作成することが可能であることを確認した．

第 6 章では，プラスチック繊維を RAC に混合し，圧縮試験，引張試験，曲げ試験などを行い，プラスチック繊維添加による RAC の性能向上を実験的に検証した．

第 7 章は結論である．

以上要するに，本論文は，再生骨材を用いたコンクリートの性能を向上させるための様々な方法を提案し，再生骨材の使用量の増加と RAC の高次利活用に貢献するとともに，環境科学の発展にも寄与するところが少なくない．よって，本論文は博士(学術)の学位論文として合格と認める．